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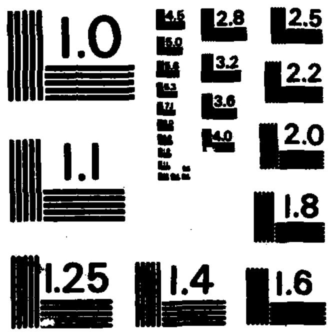

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FLAME JET DRILLING AND CHAMBERING TO GREAT DEPTHS IN CRYSTALLINE ROCK

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A flame-jet drill consuming $34m^3$ of compressed air at 20 kg/cm^2 has drilled a 40 cm diameter hole in Barre, Vermont granite to a depth of 130 meters. With a cost of less than \$10 per foot of hole it is recommended that depth capability be increased significantly.

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Figure 6. Report Documentation Page.

FLAME JET DRILLING AND CHAMBERING TO GREAT DEPTHS IN CRYSTALLINE ROCK*

SUMMARY

A flame drill powered by an internal (rocket type) burner has drilled a vertical 40cm diameter hole in Barre, Vermont granite to a depth of 130 meters. At this depth chip and water removal from the hole become unreliable. For greater depths additional compressed air would have to be used.

The equipment comprised a 14cm diameter drill 9m long using $34m^3$/min of compressed air for "low pressure" combustion with 150 l/hr of No. 2 fuel oil. The drill was supported by an umbilical bundle of the air, fuel, and cooling water hoses. This hose bundle, wrapped on a single reel, was capable of reaching a hole depth of 380m. Continuous down-hole and withdrawal at high speed rates present a great advantage over conventional discontinuous methods.

The hose reel can hold a maximum of 750m of the "low pressure" bundle and up to 1,500m of a proposed "high pressure" bundle. We recommend extending the 40cm hole to 750m at Barre under a separate Phase II proposal and to determine the capability of the process for drilling holes as small as 15cm to depths extending to 1,500m.

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* This work has been performed under Contract No. N00014-82-C-0249 for the Small Business Innovation Program of the United States Department of Defense.

Special thanks to the SULLAIR CORPORATION , Michigan City, Indiana for its significant financial support of the continuing deep drilling program and to the ROCK OF AGES CORPORATION, Barre, Vermont for the use of its quarry area as a drill site and for providing the necessary support facilities.

Additional thanks to Mr. David F. Morris of Port Washington, New York for the use of his photographs shown in Figures 5, 6, 8, 9, and 10.

DISCUSSION

This report covers a portion of our overall program to reach great depths in crystalline rock using the flame jet process. Last year, under contract to the Los Alamos National Laboratory (LANL) hot dry rock geothermal energy group we drilled a 23cm hole to a depth of over 300m in Conway, N.H. granite. Drilling speeds greater than 30m/hr were obtained at deeper levels where the rock became stressed.

The current program was initially established to extend depth capability to 1km. The cooperation of several sources would have been necessary to fund this ambitious step. One of these sources withdrew its financial commitment. A change in goal was made to investigate the drilling of much larger diameter holes to lesser depth.

Under the revised conditions it would now be possible to locate the drill site as conveniently close to Hanover as possible. We received the cooperation of the ROCK OF AGES CORPORATION who believed that its most uniform granite would be at the center of the relatively small exposed area of the formation on top of a steep hill. They cleared an area for our use, provided level pads for our heavy equipment, and delivered fuel oil and water as needed.

The importance of rock uniformity rests in the fact that flame drilling is applicable to hard crystalline rock but not to softer zones characterized by weathered or leached granite or by intrusions of non-spallable material. A concurrent drilling program at LANL is studying flame drilling using a conventional well rig. Non-spallable regions would be drilled by substituting conventional mechanical means.

The LANL effort should lead to equipment capable of reaching 6 Kilometers, or more. Such depths are necessary for economic power generation from hot dry rock. This alternative approach

requires much more expensive equipment than the umbilical support system but will be able to reach much greater depths--and, in any type spallable formation.

Where applicable, the umbilical-support system offers much greater economy. The simplicity of the required apparatus and the rapid uphole and downhole speeds possible are significant advantages. The primary aim of this Small Business Innovation Program is to determine the practical limit of the system. Several general areas of use may be defined. Hole depths to 500m or so are important in applications as diverse as oil/gas and water wells, atomic waste disposal, and seismic detection of underground blasts. At some point between 2km and 3km many granites have reached temperatures above the boiling point of water. The commercial importance of being able to drill large diameter, inexpensive holes to these depths is obvious. Thus, it is important to investigate the full capability of umbilical support. Burner and drilling information gained will be equally applicable to the LANL study.

"Low pressure" operation provides air at the conventional $9kg/cm^2$ pressure to the burner. For the Barre test this was the case. Unfortunately, low pressure air at high flow rates produce high pressure losses in the long hose lengths. Compressor output pressure was $20kg/cm^2$. To deepen the 40cm hole we'd recommend doubling the air flow. The pressure at the burner would nearly double. The line loss remains nearly the same. The compressor outlet pressure would have to increase only to $29kg/cm^2$. Small holes at high speed use much greater air pressures thus minimizing expensive line losses. In Conway, where $34m^3$ of air were also used, the burner pressure was $38kg/cm^2$ with the line loss $13kg/cm^2$.

The change in program goal to an investigation of large hole drilling would, when compared to the earlier drilling at Conway, yield important operating parameters. Several valuable things

were determined. To about the 110m depth the chips and water were steadily lifted from the hole. The average "cold gas" uphole velocity was about 270m/min. At Conway this figure was 850m/min and no lifting problems to the depth of over 300m were encountered. The required air flow to extend the Barre hole could require as much as $100m^3$/min. Such an increase could not be funded under the Phase I program; thus, further drilling was terminated.

Both the Conway and Barre holes were logged by GEARHART-OWENS to determine hole diameter and directional divergence from the vertical. At Conway, the 22cm hole slanted badly. At a depth of 210m a blockage prevented further penetration. The hole diameter increased to nearly 1m. Obviously, local collapsing had resulted. (For practical use the hole would have to have been cased.) Divergence at this level was nearly 20m toward WNW.

At Barre, the directional divergence was only 7½cm to the NW. The hole was essentially vertical. The difference between the holes was the desire at Conway to drill as rapidly as possible. The drill was positioned close to the hole bottom with little side clearance. At Barre, the drill was held well above the bottom with much increased side clearance. It is encouraging that drilling technique can control such conditions. It is best to have a hole-to-drill diameter ratio as large as possible and to feed the drill at a rate less than the maximum possible.

At Conway, the metal rim at the bottom of the drill eroded rapidly by action of the cuttings passing through the narrow annular passage between it and the hole wall. Every 30 to 40 meters the burner head had to be lifted and replaced. These units could later be repaired by conventional hard-surfacing methods. An aim of the overall deep drilling program is the maximization of drill life. At Barre, with the high diameter ratio, it appears that over 500m of hole can be drilled continuously. This may double in practice when flame-sprayed

coatings of tungsten carbide are optimized. Trial use of such coatings has been found to outlast weld overlays.

The drilling rate at Barre increased from a low of 4m/hr near the surface to nearly 9m/hr at full depth. Two factors are involved in this increase. Nearer the surface there are frequent seams with water inflow. Drilling is slowed. With depth the internal pressure of the formation increases. This increase enhances the rate of flame spalling.

Each hole consumed the same amount of reactants. At the 100m level at Conway the drilling rate averaged 16m/hr--1 3/4 times that at Barre. But the hole at Barre had a cross-sectional area 3.16 times larger. Equating the mass removal rates, the Barre drilling removed rock 75% faster. This result is not surprising. Every time we have drilled a large diameter hole--some to over 1m--the removal rate has increased dramatically with diameter. There must be a point where the cutting rate begins to decrease. We have no idea where it is.

The lower velocity flame produces a much less uniform hole diameter. That is, the areas of seaming pinch the hole diameter. At Barre the caliper log shows a maximum diameter of 62cm--a minimum of 28cm. The narrow zones are not thick. Where necessary, it should be possible to ream them by flame or mechanical means to desired size.

Costs are low wherever flame drilling can be used. For the 40cm hole at Barre, costs can be estimated:

Labor (2 men @ $20/hr)	$20.00/hr
Fuel oil (40g @ $1.05/hr)	42.00
Air (4¢/100 scf)	28.80
Amortization of Equipment	30.00
Maintenance, etc.	20.00
Direct Over head (150% labor)	30.00
	$170.80/hr
Cost of hose ($2/ft of hole)	56.00
	$226.80
Cost/ft of hole (28 ft/hr)	$ 8.10

The following portion of this discussion covers the general process of flame drilling and has been taken in part from our report covering the Conway drilling dated 4 November 1981.

* * * * * * * *

THE PROCESS

Flame-Jet drilling utilizes a compressed air-fuel oil "rocket" device--an internal burner--producing a supersonic jet stream of high temperature to impact against the rock mass. An intensely high temperature gradient is imposed extending only 1mm below the surface of the rock. (The cuttings are in the range of 600^{o}F.) Certain rock types spall rapidly due to the resulting stresses. Chips and dust are released from the advancing surface and are blown up and out of the hole.

There are many inherent advantages of flame-jet drilling compared to mechanical drilling. They include:

(1) Large annular separation of the drill from the hole wall.
(2) Cutting action requires no contact between drill and rock.
(3) High drilling speeds are possible at low cost.
(4) Extremely high energy outputs are possible to great depths.
(5) Continuous feeds possible using hoses wrapped on reels.
(6) Larger hole diameters possible with flame reaming.

Only the heating and scouring actions of the flame (3,300F for an air-fuel flame travelling at a mile per second) are utilized in flame cutting. The flame drill currently experiences serious "sandblast" erosion rates on its bottom surface with a much lower rate along its outer cylindrical walls. A continuing development program shows excellent promise to allow up to 300m of drilling before drill head replacement becomes necessary. Current drill diameters are greater than the expanded flame-jet diameter allowing direct impact of the cuttings against the lower face. It is now possible, using a small oxygen flow to help stabilize

flame reactions, to make drills with diameters smaller than the flame-jet. The jet itself blocks direct particle impact. A thin flame-sprayed coating of tungsten carbide-13% cobalt mixture protects the surface above the bottom rim of the drill.

Figure 1 graphs actual drilling data obtained using large sample blocks of Barre, Vermont granite, an Ohio dolomite, and Beria, Ohio sandstone. Taconite and strongly cemented sandstone drill similarly to granite. The reactant flows were stoichiometric.

Except for replacing worn flame drill heads, downward progress is continuous when using single lengths of hose held on reels. Retracting the drill up the hole is governed by the power and speed of the winch system. Assuming a speed of 40m/min, a drill head change for a 1,500m hole could be made in about two hours for a hole remaining essentially dry. Where the hole becomes totally filled with water the water must be completely removed when lowering the drill. For a depth of 300m in the 22cm hole this took nearly half-an-hour. For holes of great depth, water inflow should be eliminated by casing to the depth required.

Major disadvantages of the flame drilling process include its applicability only to those rocks classed as heat-spallable and the fact that even these rocks may contain zones and layers of non-spallable material.

It is probable that flame drilling can only be applied to formations of granite and other plutonics, sandstone, dolomite, and some shales and mudstones.

For deep drilling the drill with hoses is supported by a sheave held on a crane. The hoses are held on reels and a cable winch is provided. One, or more, additional trucks carry the air compressors. The entire system is mobile. Representative

photographs are at the end of the report.

At Barre, the air supply was provided by two ATLAS COPCO ER-618 two-stage reciprocating compressors. Together, they are rated at $34m^3$/min at a maximum pressure of $21kg/cm^2$. The hose reel was fabricated for the present program. The inner cylinder diameter is 1½m with the rim diameter double that. Power and controls are hydraulic with power from the drill truck. The design speed of the hoses is 0.4 to 0.8m/sec depending on the hose position on the reel. Four separate 2.54cm hoses were used in-parallel for the compressed air. One size smaller hose carried the cooling water and a 0.6cm hose for the fuel. The latter two hoses should have been larger as excessive water and fuel pressures were required. The six hoses were tightly bound together about every 3 meters with a strong rubber strap. This system gave us no trouble. The reel worked smoothly and the straps maintained bundle integrity. These hoses took the full weight of the drill system. No problems were experienced; but, deeper drilling will require a separate support cable with winch.

The burner flame is ignited above ground using a small flow of pure oxygen. Full combustion takes less than 20 seconds with an experienced operator. The hose providing this ignition oxygen is disconnected before commencing drilling. Although down-the-hole ignition is used in other applications, for drilling it adds too much complexity.

Down-feed motion should be that which will position the end of the drill from 8 inches to a foot, or more, above the bottom of the hole. Any closer approach causes a lightening of the weight of the drill string. This is detected by a read-out of the crane's main hydraulic cylinder pressure. A careful operator can keep a continuous feed motion in effect by observing this pressure gauge.

Two operators ran the complete system. One is responsible for the drill itself--the other for all ancillary equipment. Even much deeper drilling should not require more than three operators.

The rate of progress of the drill, as well as other distinctive results, are fair evidence of the type structure being encountered by the drill. Rock type identification is particularly easy. The cuttings range from powder to large beach-size sand when passing through a seam. Other evidence of a seam is the reduced cutting rate. If the seam contains water at a pressure well above atmospheric, it flows rapidly into the hole quenching any remaining flame reactions taking place in the flame-jet itself. Soot forms and water from the hole resembles ink. In two instances the water from the hole was "muddy". Clay, or other type soil, must have been encountered. The detection of seams by the above methods can only be done for open seams as tight non-weathered ones are easily passed through. Thus, it is probable that the deeper the hole the less adverse the influence of seams.

We have drilled several water wells in local granite formations. The flame-jet scours water-bearing seams increasing inflow rates to the well. Cavities of sufficient size to hold hundreds of gallons of water may be reamed by flame to serve as an adequate reservoir for domestic purposes. Such storage is particularly valuable where water inflow rates are very low.

No effort was made to complete either of the holes rapidly. We gained experience stopping and starting several times. Each time we restarted the hole was nearly full of water. The procedure used was to pass the drill below the free surface of the water. Surges of water alternated with next to no flow from the hole. The water reached heights of nearly 15 meters above ground. With increased depth, purging of the water-filled hole took progressively longer. At 100 meters, over an hour was required for the

Barre hole. The internal burner of a flame drill is not effected by underwater operation so long as the combustion pressure is greater than that of the water.

* * * * * * * *

THE PHOTOGRAPHS

The photographs give a good description of the process.

Figure 3 - This is a general view of the wooded hill top on the ROCK OF AGES CORPORATION property in Barre, Vermont. The white "logging" trucks of GEARHART-OWEN are in the fore-ground. Our "red" drill truck beyond the logging truck carries a booster compressor (not used for "low pressures") and a crane. Attached at the end of the crane boom is a 1½-m diameter sheave holding the hose bundle. The drill hangs vertically supported by the hoses. At the left is the hose reel. The bundle passes high into the air to the sheave.

Figure 4 - A closer view of the reel and air compressors is shown. The level area was prepared for us by ROCK OF AGES.

Figure 5 - The hose reel and hose bundle are shown. The hydraulic motor drives a 6-to-1 planetary reducer which powers a 3-to-1 chain drive. The maximum reel speed is 6 revolutions per minute. The smaller hoses on the ground carry the hydraulic fluid whose flow is controlled at a "remote" console kept at about 15 meters from the drilling operation. Depending on wind direction, the operator, if near the hole, can be in a miserable environment.

Figure 6 - The reel trailer is attached to the compressor truck. Water, pumped to the drill truck from about ¼km away, is pumped again to a pressure over 20kg/cm^2. Selection of a larger water hose would have reduced this. The fuel oil pressure was maintained at over 85 kg/cm^2 by a pump on the same drill truck. These hoses pass to the reel.

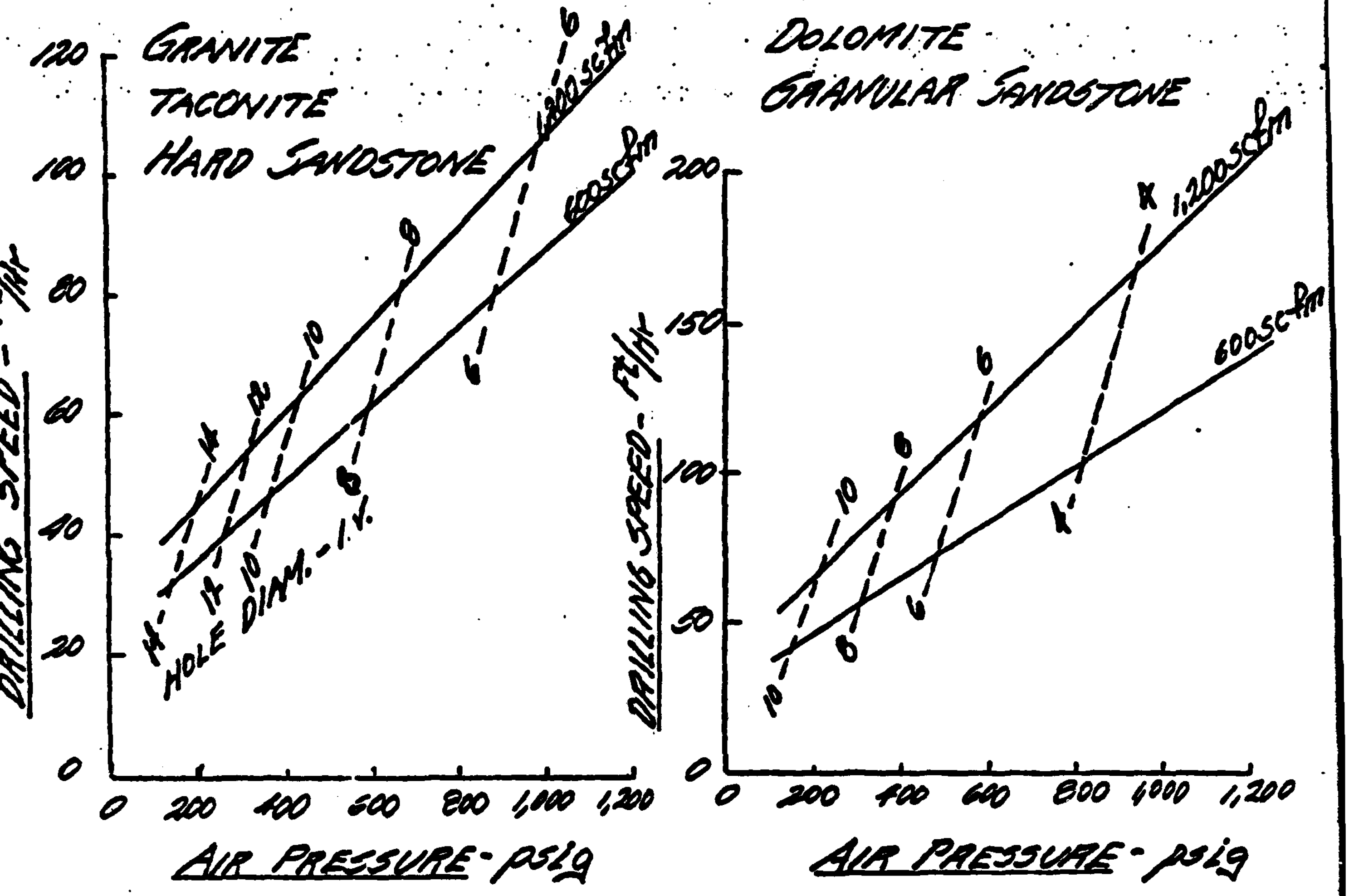
Figure 7 - The drill is held away from the hole to allow use of the auxiliary sheave for logging. The JOY booster compressor is capable of raising the air delivery pressure to 80 kg/cm^2. (It was not needed for this "low pressure" operation.) The operator's console may be seen next to the white "bucket stool". From here the up/down motion of the drill is controlled by a three-way hydraulic valve. Hydraulic fluid pressure is monitored.

Figure 8 - With drilling in progress, from a distance only a rising cloud of "steam" is seen. There is no noise other than the din of the diesel-driven compressors. Nearly all the fine dust is carried within the small water droplets thereby eliminating any dust hazard. Oxygen tanks used for start-up are chained to the side of the drill truck.

Figure 9 - The close-up view shows not only the steam but the water and larger rock chips. The wind is blowing the "steam" into the woods. There is no fire hazard once this condition is reached. Start-up can throw hot chips and even slag to as far as 30 meters away. Care must be paid to clearing the area of combustibles.

Figure 10 - A thick pile of the cuttings build up around the hole. Clearing this material away must be done once-in-a-while. A front-end loader was used. Nearly 50 tons of rock were removed during the drilling. At the surface the hole diameter is somewhat smaller than down-hole.

FIG. 1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1,200
DOLOMITE
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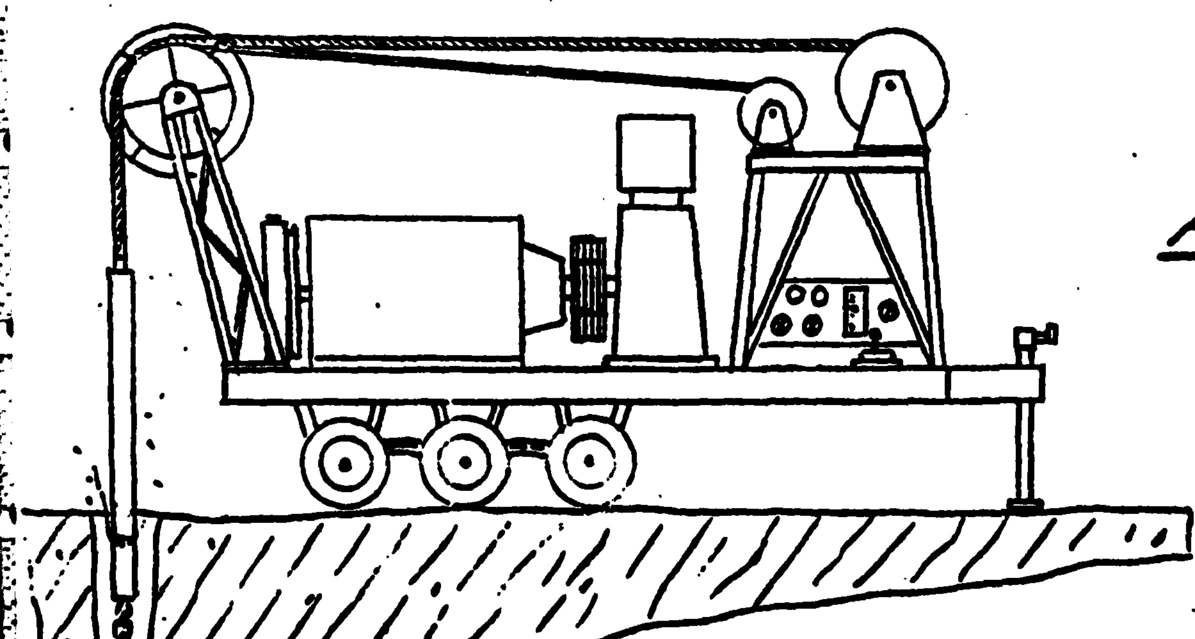

FIG. 2

FIGURE 3

FIGURE 4

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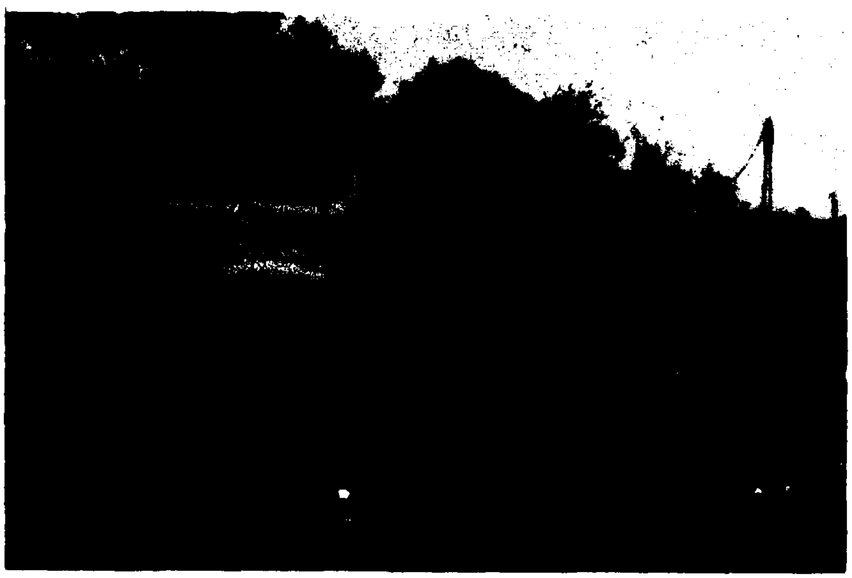

FIGURE 6

FIGURE 7

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FIGURE 9

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